THE EFFECTS OF INTERCRITICAL HEAT TREATMENTS ON THE MECHANICAL PROPERTIES OF 0.14WT%C - 0.56WT%Mn - 0.13WT%Si STRUCTURAL STEEL

P.O. Offor[a], **C.C. Daniel**, **B.A. Okorie**

Department of Metallurgical And Materials Engineering, University Of Nigeria, Nsukka, Nigeria.

[a]*Email:* *peterjoyoffor@yahoo.com.*

Abstract

Effect of intercritical heat treatment on 0.14wt%C 0.56wt%Mn 0.13wt%Si structural steel has been investigated. Specimens for single quenching and those for double quenching were prepared for intercritical heat treatment. The heat treatment of the experimental steel was based on intercritical annealing in the ferrite + austenite temperature range of the Fe - C phase diagram at temperatures 745°C, 755°C, 765°C, 775°C, 785°C, 795°C and 805°C for 1 hour at each temperature in a laboratory muffle heat treatment furnace followed by quenching in plain water to room temperature. Specimens for single quenching were subjected to the above heat treatment route once while those for double quenching were subjected to the heat treatment route twice. Afterwards the specimens that were subjected to single quenching and those that were subjected to double quenching were separately tempered in a laboratory muffle heat treatment furnace at a temperature of 200°C for 1hour and cooled to room temperature in still air. The results revealed that single quenching eliminated the yield strength, increased the tensile strength and hardness properties but decreased the ductility and notch impact toughness properties of the experimental steel. Moreover, the results also revealed that double quenching eliminated the yield strength, and produced a greater increase in tensile strength and hardness properties than single quenching but a greater decrease in the ductility and notch impact toughness properties than single quenching of the experimental steel. Tempering increased the yield strength, ductility and notch impact toughness properties of the quenched steels but decreased their tensile strength and hardness properties. The established heat treatment conditions can be useful for manufacturing steels of high strength and hardness and good ductile and notch impact toughness properties.

Keywords: intercritical heat treatment, single and double quenching, mechanical properties

Symbol notation

σ_t	tensile strength
σ_y	yield strength
δ	ductility
H	hardness
BHN	Brinnel hardnes number
a_n	notch impact toughness
s_q	single quenched sample

d_q double quenched sample
s_{qt} single quenched and tempered sample
d_{qt} double quenched and tempered sample

1. Introduction

The automotive industry aims at the production of vehicles with low weight, fulfilling high requirement concerning the safety improvement, the reduced fuel consumption and the limitation of the emission of harmful exhaust gases. In order to meet these demands, the optimization of well known materials and searching for new materials with a high ratio of strength to density and suitability for metal forming operations are still carried out. The requirements of the automotive industry are often met by micro alloyed structural steels [1 - 4]. In the modern automotive hot-rolled plates of micro alloyed steels are often used. Besides micro alloyed steel plates, cold - rolled sheets of BH - type (back hardening) and IF - type (interstitial free) structure are used [1, 5 - 8]. A special group of interest are steels of multiphase structure. They exhibit a superior strength-ductility balance compared to conventional steels. These are sheets of the ferritic-martensitic (DP - dual phase) [1, 9, 10], ferritic-bainitic structure with the retained austenite showing trip (transformation induced plasticity) effect [1, 11, 13] and complex multiphase cp-type structure (CP - complex phase). The interest in respect of the stability for metal forming operations is also connected with high - manganese steels of austenitic structure. To strengthen these steels the mechanical twinning during the technological deforming is used (TWIP effect – Twinning induced plasticity) [1, 14, 15,].

Selection of a steel grade for a particular strength level should take into account the expected loads in forming. In this way the individual advantages can be optimally exploited and the steel can also be used for difficult drawn parts. The good work hardening properties, expressed by a relatively high n - value, make dual phase steels particularly suitable for severe stretch forming. Due to their balanced ferrite and martensite contents they offer a particularly attractive combination of high strength, low yielding-to-tensile ratio, good cold formability, and weldability [16].

Table 1: Chemical composition of the steel used (wt %) with its critical temperature (calculated).

C	Mn	Si	Ni	S	AC_1 (°C)	AC_3 (°C)
0.14	0.52	0.13	0.04	0.001	725	831

Table 2: The mechanical properties of the experimental steel in its original state.

σ_y	σ_t	δ	H	a_n
N/mm^2	N/mm^2	%	BHN	J/cm^2
236.73	416.65	32.14	161	68.24

2. Objectivies of the Study

The objectives of this work are to investigate the effects of intercritical annealing temperatures, single quenching, double quenching and low temperature tempering on the mechanical properties of 0.14wt%C - 0.56wt%Mn - 0.13wt%Si structural steel.

3. Materials and Methods

3.1. Materials

The investigations were made using the specimens made from the experimental hot rolled 16mm (5/8inch) steel rod. The chemical composition and the critical temperatures of the experimental steel are given in Table 1. The mechanical properties of the experimental steel in its original as hot - rolled state are given in Table 2.

3.2. Methods

In order to design suitable heat treatment conditions, the knowledge of critical temperatures Ac_1 and Ac_3 for the austenite phase is needed. They were calculated using Andrews' equations [1, 17 - 20]. The calculated temperatures of the investigated steel are $AC_1 = 725°C$ and $AC_3 = 831°C$.

The specimens used for the present work were machined from the investigated steel. Specimens for single quenching and those for double quenching were prepared for intercritical heat treatment. The heat treatment of the experimental steel was based on intercritical annealing in the ferrite + austenite temperature range of the Fe-C phase diagram at temperatures 745°C, 755°C, 765°C, 775°C, 785°C, 795°C and 805°C for 1 hour at each temperature in a laboratory muffle heat treatment furnace and quenched in plain water to room temperature. Specimens for single quenching were subjected to the above heat treatment route once while those for double quenching were subjected to the heat treatment route twice. Afterwards the specimens that were subjected to single quenching and those that were subjected to double quenching were separately tempered in a laboratory muffle heat treatment furnace at a temperature of 200°C for 1hr and cooled to room temperature in still air. The quenched specimens were tempered to improve their ductility and notch impact toughness. After the heat treatment of the specimens, tensile tests were carried out at room temperature using 10 ton universal testing machine. Brinell hardness testing method was used to determine hardness while Charpy impact testing machine was used for the determination of the notch impact toughness.

4. Results and Discussions

The results of the measurements made are tabulated in Tables 2 - 6.

A critical examination of Tables 2 - 6 reveals that single quenching eliminated the yield strength increased the tensile strength and hardness properties but decreased the ductility and notch impact toughness properties of the experimental steel. Moreover, the tables also revealed that double quenching eliminated the yield strength, and produced a greater increase in tensile strength and hardness properties than single quenching but a greater decrease in the ductility and notch impact toughness properties than single quenching of the experimental steel. The mechanical properties of dual-phase steels arise from structural features, that is the fine dispersion of hard martensite particles in a ductile ferrite matrix and all the related phenomena that accompany the "coexistence" [21]. The contributions of hardening mechanisms in martensitic structure according to [17, 22] include the solid solution substitution element hardening, the precipitation hardening, the primary austenitic grain size hardening and the martensite morphology hardening. The dominant hardening effect of martensite in dual phase steels is the carbon concentration in martensite. It is relatively difficult to formulate regression equations for the contributions of the individual hardening mechanisms in martensite, as it is possible for polygonal ferrite, since it is impossible to separate individual hardening mechanisms [22].

The yielding and the work hardening behaviour have been interpreted in terms of the high dislocation densities and residual stresses arising in ferrite, as a consequence of the volume expansion associated with austenite to martensite transformation. The strength of dual-phase steels was found to be dependent primarily upon the volume fraction and the carbon content of martensite; solid solution strengthening of ferrite may also contribute to strength [21]. Dual phase steels have been designed to have low carbon with or without alloying elements and heat treated or hot rolled to have martensite volume fractions rarely exceeding 15%, because beyond this percentage, formability of dual phase steels is badly affected [23]. The mechanical properties achieved from intercritical heat treatment are functions of the annealing temperature, higher intercritical annealing temperatures gave higher tensile strength and hardness properties but lower ductility and notch impact toughness properties (see Tables 2 - 6). The tensile strength and hardness properties increased with rising of the annealing temperature (because the martensite content

Table 3: Strength properties of the heat treated steel specimens..

T °C	σ_{ysq} N/mm^2	σ_{ydq} N/mm^2	σ_{ysqt} N/mm^2	σ_{ydqt} N/mm^2	σ_{tsq} N/mm^2	σ_{tdq} N/mm^2	σ_{tsqt} N/mm^2	σ_{tdqt} N/mm^2	
745	-	-	210.98	217.71	494.69	505.28	466.38	473.17	-
755	-	-	230.13	234.86	515.74	522.44	486.16	498.64	-
765	-	-	265.81	273.54	543.51	553.71	500.12	524.35	-
775	-	-	285.66	294.66	568.41	599.83	545.8	562.84	-
785	-	-	310.46	316.52	650.17	658.36	611.33	617.19	-
795	-	-	340.27	350.49	672.94	696.45	636.48	660.21	-
805	-	-	357.63	453.97	713.19	737.97	676.32	704.73	-

Table 4: Ductility properties of heat treated steel specimens.

T °C	σ_{sq} %	σ_{dq} %	σ_{sqt} %	σ_{dqt} %
745	10.31	7.18	14.74	12.01
755	9.48	6.12	13.91	11.86
765	7.99	5.85	13.24	10.29
775	7.54	5.48	12.17	9.77
785	6.52	4.72	10.89	8.51
795	5.84	3.76	9.72	7.64
805	4.02	2.72	8.21	6.12

Table 5: Hardness properties of heat treated steel specimens.

T °C	H_{sq} BHN	H_{dq} BHN	H_{sqt} BHN	H_{dqt} BHN
745	179	194	142	157
755	191	207	155	167
765	203	215	164	176
775	212	226	175	188
785	220	231	189	200
795	231	240	201	209
805	239	247	211	221

in the structure is increasing), with decrease of ductility and notch impact toughness [17, 24]. The higher the annealing temperature selected in the intercritical temperature zone, the more austenite forms and transforms to martensite, but the less carbon content in this martensite [23]. The increase in hardness, with the increase in intercritical annealing temperature has been attributed to the increase in volume fraction of martensite (austenite before quenching) which is a strong load-bearing phase in ferrite-martensite dual phase steels. Increasing the volume fraction of martensite decreases the interface of the ferrite and martensite and therefore, the number of suitable places for nucleation and propagation of cracks decreases [23].

The excellent ductility reported for most of the dual phase steels is the combined result of many factors. Among them are the volume fraction and the carbon content of martensite, topological parameters such as the martensite grain distribution in the ferrite matrix, the alloy content of ferrite, the dislocation density in ferrite, the presence of carbides and/or retained austenite [22].

Tempering may be applied as part of the process in some continuous annealing lines, after water-quenching in intercritical treatment, to regulate the properties of the dual phase steel. After tempering at low temperatures, the yield strength increases. Discontinuous yielding returns only to the steels containing only low volumes of martensite. When tempering at high temperatures, the yield strength decreases but discontinuous yielding appears in all steels. The tensile strength decreases while post uniform and uniform elongations increase due to change in hardness of martensite [22].

5. Conclusions

Conclusively, strength and hardness values increased with an increase in intercritical annealing temperatures. Ductility and notch impact toughness decreased with an increase in intercritical annealing temperatures. The tempered steel has yield strength values which increased with increase in intercritical annealing temperatures. Tempering gave rise

Table 6: Notch impact properties of heat treated steel specimens.

T °C	an_{sq} J/cm^2	an_{dq} J/cm^2	an_{sqt} J/cm^2	an_{dqt} J/cm^2
745	9.81	8.74	84.23	77.61
755	9.24	7.91	78.18	71.36
765	7.01	6.84	72.97	65.27
775	6.45	6.00	67.34	60.92
785	5.85	5.23	64.74	54.29
795	5.20	4.76	59.89	49.17
805	4.84	3.98	52.46	45.66

to a decrease in tensile strength and hardness and an increase in ductility and notch impact toughness of the as hot rolled steel. Tempered steels presented the better compromise between strength, hardness, ductility and notch impact toughness. Single quenching eliminated the yield strength, increased the tensile strength and hardness properties but decreased the ductility and notch impact toughness properties of the experimental steel. Double quenching eliminated the yield strength, and produced a greater increase in tensile strength and hardness properties than single quenching but a greater decrease in the ductility and notch impact toughness properties than single quenching of the experimental steel. Tempering increased the yield strength, ductility and notch impact toughness properties of the quenched steels but decreased their tensile strength and hardness properties. The established heat treatment conditions can be useful for manufacturing steels of high strength and hardness and good ductile and notch impact toughness properties.

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